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A Serendipitous, Long-Term Infiltration Experiment: Water and Tritium Circulation Beneath the CAMBRIC Ditch at the Nevada Test Site

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Abstract

Underground nuclear weapons testing at the Nevada Test Site introduced numerous radionuclides that may be used to characterize subsurface hydrologic transport processes in arid climates. A sixteen year pumping experiment designed to examine radionuclide migration away from the CAMBRIC nuclear test, conducted in groundwater beneath Frenchman Flat in 1965, gave rise to an unintended second experiment involving radionuclide infiltration through the vadose zone, as induced by seepage of pumping effluents beneath an unlined discharge trench. The combined experiments have been reanalyzed using a detailed, three-dimensional numerical model of transient, variably saturated flow and mass transport, tailored specifically for large-scale and efficient calculations. Simulations have been used to estimate radionuclide travel and residence times in various parts of the system for comparison with observations in wells. Model predictions of mass transport were able to clearly demonstrate radionuclide recycling behavior between the ditch and pumping well previously suggested by isotopic age dating information; match travel time estimates for radionuclides moving between the ditch, the water table, and monitoring wells; and provide more realistic ways in which to interpret the pumping well elution curves. Collectively, the results illustrate the utility of integrating detailed numerical modeling with diverse observational data in developing accurate interpretations and forecasts of contaminant migration processes

1. Introduction

Between 1957 and 1992, over 800 underground nuclear tests were conducted at the Nevada Test Site (NTS) in Southern Nevada, roughly a third of which were beneath the regional water table (USDOE, 2000). In recent years, there has been increasing technical and regulatory interest in the nature and extent to which residual test-related radioactivity can contaminate groundwater. (USDOE, 1997). At the NTS alone, the total radiologic inventory of underground nuclear tests is estimated to contain over 10^8 curies (Ci) of radioactivity associated with 43 long-lived radioisotopes (Bowen, et al., 2001).

Efforts to study how radioactivity is released into groundwater must initially focus on the near-field environment surrounding a test, the associated alterations generated by nuclear explosion effects, and the amount and form of radioactivity distributed in this area. Alteration effects include, for example, the blast cavity formed around the test working point, the collapsed, in-fallen rubble chimney formed above the cavity, newly fractured or other impacted rock surrounding the cavity, and the aggregate mass of melt glass or other form of melted rock typically found in the bottom of the cavity (Tompson et al., 2002). Radionuclides associated with the test are derived from the original materials in the device, nuclear reactions connected with the explosion, and activation products created in the geologic medium. They are known to accumulate in the melt glass during its formation and in the rubble and near field zones surrounding the cavity and chimney, all roughly as a function of elemental vapor pressure, cooling history, and other features of the test location, such as local saturation conditions (Smith, 1995).

Processes that lead to radionuclide contamination in groundwater include their direct accumulation as soluble species in groundwater that reinvades the cavity and rubble environment after a test, or through processes associated with the dissolution of melt glass. These releases are collectively called the hydrologic source term (HST) for a test, and may evolve for hundreds or more years as a source of contamination.

Early efforts to characterize these mechanisms focused on analyses of data collected from diagnostic bore holes drilled into test cavities and chimneys after tests (e.g., Borg et al., 1976). These surveys included information on the nature and physical condition of the altered rocks in the cavity and chimney, the radiologic content of water and rock samples collected in these areas, as well as bore hole temperature and residual radioactivity profiles. Later activities included hydrogeologic and pumping investigations, laboratory studies of radionuclide sorption and melt glass dissolution, and application of numerical simulation models to codify the evolving and collective understanding of these processes (e.g., Burbey and Wheatcraft, 1986; Ogard et al., 1988; USDOE, 1997; Guell and Hunt 2003; Tompson et al., 1999, 2002; Pawloski et al., 2001; Wolfsberg et al., 2001; Tompson et al., 2002).

The objectives of this paper are to analyze a series of simulations associated with a pumping experiment conducted adjacent to the CAMBRIC underground test in the context of an evolving body of hydrologic, isotopic, and groundwater age related data. The experiment itself involved pumping groundwater continuously for 16 years as a means to elicit information on radionuclide movement away from the test. It subsequently gave rise to a second serendipitous experiment involving the infiltration of discharged effluent through a 220 m deep vadose zone at the site. Despite original views to the contrary, the collective data and simulations presented here suggest that much of this discharge was able to reach the groundwater and become recaptured by the well, often through several recapture cycles. These analyses are forcing a reinterpretation of the original pumping well recovery curves and are shedding light on a second and more widespread source of radionuclide contamination in the groundwater underlying the surface discharge areas, well beyond the original test vicinity.

In the subsequent sections, we review the experimental history in additional detail; provide a synopsis of the most recent groundwater flow model at the site; and present modeling analyses of mass transport in the system, including both test related radionuclides and apparent groundwater age, all in the context of the site observations. These results provide valuable insights into the processes occurring at the site, and to similar processes occurring elsewhere: both to understand the role of the vadose zone on movement of water in arid environments and to understand the migration of radionuclides in the environment.

2. History of Experiment

The CAMBRIC nuclear test was conducted beneath Frenchman Flat at the NTS on May 14, 1965 (USDOE, 2000). The detonation point was in heterogeneous alluvium, 294 m beneath the ground surface and approximately 74 m beneath the local, relatively flat water table (Figure 1). The announced energy-equivalent yield of the test was 0.75 kilotons (kt). The explosion created a detonation cavity approximately 27 m in diameter that was subsequently filled in by collapsed alluvium and later re-saturated with groundwater (Bryant, 1992; Hoffman et al., 1977; Carle et al., 2007). The slumped chimney above the cavity, from which the collapse occurred, is believed to extend above the water table, but not to the ground surface.

2.1 The Original Radionuclide Migration Experiment

In October 1975, approximately 10 y after the detonation, groundwater adjacent to the CAMBRIC test cavity was pumped steadily for 16 y, with a few short interruptions, in order to elicit information on test-related radionuclide migration (RNM) in the saturated zone (Hoffman et al., 1977; Daniels, 1982 and Bryant, 1992). As shown in Figure 1, the pumping well (RNM-2S) is located approximately 91 m south of the emplacement hole (U-5e) and is screened over an approximately 25-m interval between depths of 316 and 341 m, slightly below the elevation of the cavity. An existing monitoring well (UE-5n), 529 m away from the pumping well and 106 m perpendicular to the ditch, is screened in the saturated zone over a 3-m interval just below the water table.

The pumping well effluent was regularly monitored for its radionuclide content. The effluent was discharged to an unlined ditch (Figure 1) and allowed to flow towards the Frenchman Lake playa, approximately 1.6 km to the southeast. Over the 16 y of pumping, extensive growth of saltcedar and cattail – both invasive, nonnative shrubs – occurred along the ditch.

Radionuclides regularly observed in the effluent included tritium (or ^{3}H, occurring in water as the molecule HTO), ^{36}Cl, ^{85}Kr, and ^{129}I (Bryant, 1992). Sporadic observations of ^{106}Ru and ^{99}Tc were also made. Figure 2 shows the tritium activity and ^{36}Cl concentration measured in the effluent between 1975 and the cessation of pumping in 1991 (all data are decay corrected to May 14, 1965). An isolated tritium measurement made in 2000 is also shown. The recovery curves appear to reflect a relatively complete capture of tritium and ^{36}Cl contamination, which are generally quite mobile in groundwater. Similar breakthrough behavior was observed for ^{85}Kr and ^{129}I (see Bryant, 1992). Analyses for relatively immobile species such as ^{90}Sr, ^{137}Cs, and ^{238,}

^{239}Pu were performed but these species were either not detected above background levels or associated with significant measurement uncertainties. Detection of other radionuclides was not formally pursued during the pumping test, although test-related ^{14}C was later measured in the pumping well in 2000 (Tompson et al., 2006), indicating its apparent co-migration with other mobile radionuclides that were pumped and discharged into the ditch. A few contemporary measurements of ^{237}Np have been made but are also associated with significant measurement uncertainty (Carle, et al., 2007).

The first arrival of tritium and ^{36}Cl were not observed until after more than two years (900 d) of pumping, and only after the initial pumping rate (300 gpm, or 1,635 m^3/d) was doubled (to 600 gpm, or 3,270 m^3/d) after 700 d. The first arrival times for ^{85}Kr and ^{129}I (not shown) were generally similar. The peak tritium concentration was observed in 1981. The peak concentration of ^{36}Cl occurred somewhat earlier, while peak concentrations of ^{85}Kr and ^{129}I (not shown) were substantially delayed. Measured concentrations of ^{106}Ru and ^{99}Tc were too infrequent to allow similar comparisons. Differences in the shapes of these profiles have been attributed to detonation effects that affect the initial distribution of different residual radionuclides (Bryant, 1992; Guell and Hunt, 2003; and Tompson et al., 2002), as well as slight differences in their individual mobilities in groundwater.

2.2 The Serendipitous Infiltration Experiment

During the RNM experiment the infiltration of contaminated ditch effluent into the 220 meters of unsaturated alluvium was not perceived to constitute a significant threat with regard to recontamination of groundwater. This concern was challenged in the mid 1980s and early 1990s with a series of soil moisture and water quality measurements in which the infiltration of water, tritium and ^{36}Cl were measured horizontally to about 7 m and vertically to at least 30 m beneath and away from the ditch (Buddemeier et al., 1991 and Ross and Wheatcraft, 1994; see Figure 1). Measurements of the ditch flow rate between the pumping well and Frenchman Lake indicated that a loss of approximately 175 gpm (or 954 m^3/d, roughly one third of the upstream flow rate) occurred over an approximately 1,000-m distance (Bryant, 1992; Mizell et al., 2005). This loss amounts to approximately 0.01 kg-water/s per meter of ditch length (yet was estimated by Ross and Wheatcraft (1994) to be closer to 0.02 kg-water/s per meter of ditch length). Small diurnal fluctuations in these flow rates have been observed and attributed to daily transpiration behavior in the saltcedar and cattails. Transpiration of tritium into plant fibers has been documented by Love et al. (2002). Based upon these observations, it had been suggested that infiltrated water (and tritium) could reach the water table in approximately 9 years (Bryant, 1992).

Between 1991 and 1993, regular tests of groundwater in monitoring well UE–5n began to show rising levels of tritium at the water table (Figs. 1 and 4), apparently confirming that infiltrated radionuclides have reached groundwater after transiting the unsaturated alluvium (Davisson et al., 1994). These data suggested a 13- to 15-year transit time for tritium to move vertically from the ditch to the water table and then horizontally to the monitoring well. The measurements were initially made on bailed samples taken from the well, yet were made on pumped samples through 2002 (Rose et al., 2002). Notably, there was no detection of ^{14}C or ^{85}Kr in the well, suggesting their preferential volatilization in the ditch or retention in the unsaturated zone.

Between 2000 and 2002, a tritium-based age-dating analysis of groundwater collected in UE-5n suggested that 3 to 5 y of this transit time occurred solely in the vadose zone (Tompson et al., 2006). In addition, groundwater collected from the original pumping well (RNM-2S) in 2000 produced ages close to 20y, far less than the 35 years dating back to the CAMBRIC test. These data suggested a dilution effect produced when portions of the pumping well effluent, once discharged, percolated to the saturated zone to be eventually recaptured by pumping well RNM-2S. In this process, accumulated ^{3}He produced from the decay of tritium in the saturated zone was lost to the atmosphere once pumped, reducing the apparent age of the extracted water parcel, and lowering the overall age of recaptured water upon recirculation. Unpublished groundwater age data collected from RNM-1 at the same time also suggest that recirculation pathways in this cycle reentered the CAMBRIC cavity before recapture. The existence of recirculation is further supported by $^{18}O/^{16}O$ and D/H isotope data that clearly show evaporative enrichment during water recycling. Thus, the role of the vadose zone under the flowing conditions of the ditch was non-trivial as evidenced by a significant return of mobile radionuclides to groundwater.

2.3 Wells ER5-4 and ER-5-4#2

In 2001, wells ER-5-4 and ER-5-4#2 were installed near CAMBRIC to gather additional hydraulic, chemical, and geologic information about the alluvium and deeper geologic units in central Frenchman Flat. These wells are located approximately 365 m northeast of RNM-2S (Figure 1). In 2003, a Multiple Well Aquifer Test (MWAT) was conducted in using the original pumping well (RNM-2S) to observe drawdown and recovery behavior in these wells as well as in UE-5n and RNM-1 (Stoller Navarro, 2004). The MWAT provided a basis to measure layer-scale aquifer parameters and improve and calibrate local groundwater flow models. It is notable that the drilling effluent from the construction of well ER-5-4 revealed a coherent tritium signature (~ 5,000 pCi/L) in the saturated zone between depths of 290 to 310 m, similar to the depth of the CAMBRIC device. Although these data have been considered “anomalous” (IT Corporation, 2001), and no similar measurement was detected in the construction of nearby well

ER-5-4#2 (IT Corporation, 2003), the location and continuity of the signal do not necessarily seem inconsistent with a tritium recirculation process.

3.0 Models

Extensive studies and analyses of radionuclide migration in groundwater between the CAMBRIC cavity and the pumping well have been conducted, both during and after the original RNM experiment (Hoffman et al., 1977; Bryant, 1992; LATA, 1982; Daniels, 1982; Burbey and Wheatcraft, 1986; Guell and Hunt, 2003; Ogard et al., 1988; and Tompson et al., 1999, 2002). Two more recent studies have also focused on migration behavior in the vadose zone, between the ditch and the water table (Ross and Wheatcraft, 1994; Tompson et al., 2006). Many of these were simplified or idealized in various respects, such as with regard to their dimensionality, degree of chemical complexity, or representation of vadose zone flow processes.

In this paper, an application of a sophisticated model of groundwater flow and tritium transport to both the saturated and unsaturated portions of the CAMBRIC system will be described. The model is three-dimensional, transient, very large in size, yet small in scale to explicitly account for detailed subsurface heterogeneity, and is able to relax many of the simplifying modeling assumptions employed in previous work. The purpose of this model is to explore more carefully the roles of ditch recirculation and the vadose zone on tritium transport, the eventual redistribution of the well effluent, and their collective potential impacts on longer-term transport of all test-related radionuclides, in general, in groundwater as a result of the pumping experiment. Although only tritium is considered here, previous work (Carle et al. 2007) considered the migration of over 30 other radionuclides in this system.

3.1 Saturated-Unsaturated Model Domain

The domain used to develop the updated model is a 3D prismatic block underlying the rectangular area illustrated in Figure 3. This block is 7,500 m long, 6,000 m wide, and 1,000 m deep and is rotated about a vertical axis N41°W so that its longer edge is roughly parallel with the CAMBRIC ditch. It extends vertically from the ground surface through the vadose zone, and into the saturated zone to a point approximately 700 m below the CAMBRIC test cavity. The ends of the model domain were extended some distance away from the CAMBRIC test as a means to remove boundary influences on drawdown behavior from pumping and also to specify observed head conditions at various wells on the boundary.

3.2 Overall Modeling Approach

Three levels of detail were used to describe the geologic structure in the model domain (Figure 4), as needed for different parts of the modeling effort (Tompson et al., 2005; Carle et al., 2007). The outermost level (A) is based upon a basin-scale hydrostratigraphic model developed for Frenchman Flat that includes sequences of alluvium and playa confining units, vitric and welded tuffs, and a deeper carbonate aquifer, each of which is associated with individual flow and transport parameters (Bechtel Nevada, 2005). The middle level of detail (B) includes layered subdivisions in the larger alluvial units near CAMBRIC and numerous altered features in the vicinity of the test itself, such as cavity and collapsed chimney zones. Each of these features is also associated with unique flow and transport parameters. The finest level of detail (C), which may or may not be included in every simulation, utilizes a “nested grid” approach to specify heterogeneous flow and transport properties within the alluvial layers and altered units closest to CAMBRIC (specifically, within in a smaller 2,200 x 600 x 500 m region), while retaining the uniform properties in layers associated with the (A) or (B) representations in more distant parts of the domain. This was done in such a way that the "effective" property values associated with the heterogeneous portions of the domain matched their uniform counterparts specified at the (A) or (B) levels of detail (Tompson et al., 2005; Carle et al., 2007).

The overall flow and transport model approach evolved over a sequential series of simulations to support, in order, calibration, process model evaluation, and model assessment activities, respectively. These models provided parameter values and confidence in the model process description and as such are summarized here very briefly. Steps along the path included

(1) An isothermal flow calibration to ambient (background hydraulic gradient) and stressed (the MWAT pumping test) conditions within the saturated portion of the layered and altered system (A and B, above),

(2) Additional non-isothermal flow simulations in the saturated portion of the A and B system to assess the impacts of residual test heat on groundwater flows in the cavity area, and

(3) A series of isothermal, variably saturated flow and mass transport simulations in the detailed system (A, B, and C, above), using properties and specifications consistent with the calibration results in (1) and conducted under both ambient and transient conditions associated with the RNM pumping experiment between 1975 and 1991. These simulations addressed both saturated flows beneath the water table and infiltration processes in the unsaturated zone using a Richards' equation approach.

The calibration simulations in (1) were used to define or refine effective, anisotropic hydraulic conductivity specifications in the sub-layers and altered zones near CAMBRIC and were guided by a variety of additional mineralogic and hydrogeologic data from the area. They were subsequently used to drive a simple tracer transport model to further assess the calibration to the early part of the tritium recovery curve acquired in the RNM experiment (Figure 2).

The non-isothermal simulations in (2) were conducted to assess whether hydrothermal flows, as potentially influenced by residual test heat, would occur and be important in any of the subsequent simulation scenarios (e.g., as in Tompson et al., 2002). The results indicated minimal impacts to the flow system over the first 5 years after the test and confirmed that the more substantive, variable saturated simulations in (3) could be made under isothermal conditions. Typical hydraulic conductivity values for the alluvial units ranged from 1 to 4 m/d, with a physical (horizontal to vertical) anisotropy of 2. Hydraulic conductivity values in the tuff and confining units had values between 1E-3 to 34 m/d. Complete model parameters may be found in Carle et al (2007, see table 4.5)

As covered in more detail in the following sections, the variably saturated flow simulations in Step (3) were conducted specifically to assess the migration of tritium, between the CAMBRIC cavity area and the pumping well in the saturated zone, between the ditch, playa, and water table in the unsaturated zone, and in the broader saturated regime, both near and away from the testing and ditch recharge areas. The flow simulations here involved the specification of separate spatially correlated hydraulic conductivity (K) distributions in both the near-field alluvial sub-layers and many of the altered zones near the test working point (Carle et al., 2007). Typical geostatistical specifications in these areas included standard deviations of ln(K) between 1 and 1.5, horizontal ln(K) correlation lengths between 14 and 40 m, vertical ln(K) correlation lengths of 6 m, and geometric mean conductivities (K_G) between 1E-03 and 15 m/d. In areas where flow becomes partially saturated, the Van Genuchten model was used to define the moisture curve and relative permeability relationships (α=1 m^{-1}; m = 0.5) in Richard's Equation. Complete model parameters may be found in Carle et al (2007, see table 4.5). Although the primary simulations in this system will be confined to a single, base-case realization of the ln(K) distribution, an initial series of simulations was conducted using a number of realizations as a means to examine the influence of heterogeneity in controlling tracer breakthrough at RNM-2S and water level drawdown at well UE-5n, both under pumping conditions at RNM-2S. From these simulations, a base-case replicate that best reproduced these observations was selected to perform all subsequent simulations in a "single realization" mode. Results of these simulations are discussed below in Section 5.1.

4. Variably Saturated Flow Simulations

The model discussed in this paper is a variably saturated flow model (Step 3 above) based upon a nested computational grid built within the model domain identified above. A coarse grid was used in the peripheral regions of the domain (200 x 300 x 50 m computational cell) while the inner region surrounding the ditch, playa, and test area was represented by a fine grid (4 x 4 x 2 m computational cell) in order to resolve local heterogeneity in the properties of the alluvium sub layers. There are a total of 24,197,936 computational cells in the overall computational model domain. The parametric specifications of hydraulic conductivity, porosity, and moisture retention used in these simulations, as developed under Steps 1, 2, and 3 above, are described in Tompson et al. (2005) and Carle et al. (2007).

Fluid flow in this system was simulated by the ParFlow code, a parallel and highly efficient variably saturated flow model that also includes an integrated capability to simulate overland flow (Ashby and Falgout, 1996; Jones and Woodward, 2001; and Kollet and Maxwell, 2006). For Richard's Equation, ParFlow uses a cell-centered finite difference approach in space, an implicit backward Euler scheme in time, and a matrix-free Newton-Krylov methodology based upon multigrid preconditioning to solve the resulting discretized system of nonlinear equations.

4.1 Flow Model Description

The variably saturated flow model was run for a 1,000-year period to simulate flow and support tritium transport calculations for that same period following the CAMBRIC test. This was done in five operational phases (described below), with the flow and tritium configurations at the end of each phase serving as initial conditions for the next phase. In all cases, combinations of fixed pressure and no-flow boundary conditions were used along appropriate side, top, and bottom perimeter boundaries, as developed and refined in the calibration and assessment steps outlined earlier. Specified flux conditions underneath the ditch and playa discharge areas, honoring the measured infiltration rates, were also applied during the periods of pumping.

(1) In Phase 1, steady-state groundwater flow, in the absence of pumping or infiltration recharge, was simulated as a means to influence tritium migration away from the initial RST configuration in the CAMBRIC cavity system (described below) between the time of the test (1965) and the onset of the RNM pumping experiment (a period lasting 10.4 y).

(2) In Phase 2, the RNM pumping well was operated at a rate of 300 gpm for a period of 700 d. During this period, infiltration along the ditch and playa impoundment areas was applied according to the measured pumping rates, as described above. This flow field would serve to drive tritium toward the pumping well.

(3) In Phase 3, the pumping rate at the RNM well was increased to 600-gpm and operated steadily for an additional 4,853 d, completing over 15 y of pumping in 1991. During this period,

the specified rates of infiltration along the ditch and playa impoundment areas were modified to reflect the added discharges from the RNM well. This time period corresponds to the observed radionuclide elution curves shown in Figure 2.

(4) Following the cessation of pumping, Phase 4 covers a 40-y recession period (1991-2031) in which residual saturation in the unsaturated zone underlying the ditch and lake discharge areas was allowed to drain, and the accumulated or “mounded” water on the water table was allowed to dissipate. Over this period, the flow system effectively relaxed to the ambient, steady state condition found in Phase 1. The early part of this time period (1991-present) corresponds to the observed radionuclide arrival times in monitoring well UE-5n shown in Figure 2.

(5) In Phase 5, the steady-state flow model result of Phase 1 is assumed to be applicable over the remaining 900+ years of the simulation period, and will serve to influence radionuclides movements away from both the cavity and ditch discharge areas as developed previously under Phases 2, 3, and 4.

4.2 Flow Model Results

Figure 6 compares observed water levels in well UE-5n with those predicted by the flow model simulation (data before 1985 were deemed unreliable, due to measurement and surveying issues). The ambient water levels obtained in Phase 1 of the simulation differ only slightly from the observed static levels. During the Phases 2 and 3 of the simulation, corresponding to the operation of the pumping well, three distinct stages of the response in UE-5n can be seen. The first two correspond to the onset and eventual increase in the pumping rates, while the third stage, beginning around 1980, corresponds to compounding effects associated with both pumping and the arriving infiltration front at the water table. During Phase 4 of the simulation, following the cessation of pumping in 1991, we see a more pronounced mounding effect followed by a gradual decline back toward the original ambient level.

Figure 7 shows a time series of saturation levels on a vertical plane under the centerline of the ditch obtained from Phases 2, 3, and 4 of the flow simulation. The images show the developing saturation front advancing from the ditch to the water table between 1986 and 1982 (upper left to lower left). Spatial variation in the saturation clearly develops in response to soil heterogeneity (as indicated in the lower right part of figure), yet saturation remains fairly steady between 1982 and 1990 indicating the system has reached a quasi-steady-state of saturation. Infiltration in the system appears to occur along preferential, high conductivity channels, as evidenced by a large number of zones of completely saturated (perched) water. Moreover, some areas of high saturation are clustered in a lower permeability playa unit that extends from the ground surface downward on the right side of the figure. This unit also takes the longest to drain as evidenced by the relatively large saturation values persisting eight years after the cessation of pumping (middle left panel, 2000).

5. Mass Transport Simulations and Discussion

The variably saturated flow model was used to drive tritium migration from an initial source configuration near the CAMBRIC cavity through all 5 phases of the simulation, including capture in the RNM pumping well and reintroduction into the vadose zone under the ditch.

Tritium migration in the variably saturated flow fields was simulated using the SLIM code, a highly efficient model based upon a Lagrangian particle-tracking methodology tailored for both fully and partially saturated conditions (Maxwell and Tompson, 2006). Particle-tracking methods have been widely applied in subsurface transport problems (e.g., Tompson and Gelhar, 1990; LaBolle et al., 1996; Maxwell and Kastenberg, 1999; Maxwell et al., 2007). In SLIM, particles are moved individually from an initial configuration over a sequence of optimized time steps – unique for each particle – to a succession of common times when information from all particles is collected and processed. In this process, particles may be split into multiple particles as a means to increase the “particle resolution” in areas of low particle density. This has been shown to improve efficiency and accuracy at low concentrations (Tompson and Dougherty, 1996).

The initial condition for tritium distribution involves the allocation of an estimated tritium inventory associated with the CAMBRIC test into groundwater occupying an 18-m radius spherical volume surrounding the test working point, all at a time just after the test when groundwater has returned to the cavity. This “exchange” volume represents portions of the altered geologic media associated with the test, and incorporates a 13.4-m radius spherical test cavity in its center, an outer spherical shell of crushed alluvium, and an in-fallen chimney zone withn and directly above the cavity (e.g., Tompson et al., 2002, 2005; Carle, et al., 2007). The estimated tritium inventory for this model is 2.08 moles, decay corrected to the test date, May 14, 1965, as reported by Hoffman et al. (1977).

5.1 Initial Mass Transport Results

Initially, a series of abbreviated mass transport simulations was pursued to examine the sensitivity of transport to heterogeneity and its influence in controlling tracer breakthrough at the pumping well. These simulations took into account the well-pumping scenario but excluded, for computational efficiency, infiltration and recharge under the ditch and playa discharge area. Fifteen realizations of the hydraulic conductivity field within the high-resolution area of the model were generated and used to develop a flow and transport model to yield a breakthrough of tritium at RNM-2S over a 25 year time period, with all other parametric specifications outside of the high resolution area remaining at their fixed, calibrated levels. Figure 8a shows the 15 breakthrough curves obtained in these simulations, along with their average and the measured data. Two realizations provided equally good fits to the observations (Figure 8b) but only one (R6) provided an equally good fit to the observed drawdown in the pumping well and was chosen to complete the transient flow model for use in all subsequent migration simulations.

5.2 Final Mass Transport Results

Following the initial simulations, a final series of mass transport simulations based upon the R6 realization was pursued to examine tritium transport over the 1,000-year flow scenario, under all 5 transient phases of the flow field outlined earlier. These simulations took into account the well-pumping scenario, and selectively included ditch infiltration, recharge under the ditch and playa discharge area, and recapture, if any, of tritium that has migrated back to the pumping well.

In Figure 9, four tritium elution profiles obtained over a 25-year period are shown from (1) measured data (as in Figs. 2 and 8) and simulations that (2) excluded ditch recharge (as in Figure 8b), (3) included ditch recharge and allowed for recirculation, and (4) were based upon ditch recharge only, using the measured elution curve as input with no initial cavity source, to assess the raw effect of recirculation. These results serve to illustrate the existence of recirculation suggested in isotopic measurements by Tompson et al. (2006) and the magnitude of its effect on the breakthrough curve, clearly visible after the 18-y mark.

5.3 Additional Discussion

Figure 10 shows several snapshots of the tritium distribution during the pumping and recession phases of the pumping experiment simulation. Clearly, the pumping experiment and ditch discharge activities served to disperse the tritium over a larger volume of groundwater as might have otherwise occurred in the absence of pumping experiment altogether. The figures show again the apparent recirculation from the ditch, to the water table, and back to the pumping well.

Based upon the results in Figure 10, the pumping well developed a capture zone encircling much of the infiltration “shadow” under the ditch but none of the infiltration “shadow” underneath the playa. The size of the capture area at the water table ensured that the travel times back to the well would be widely distributed, with tritium infiltrating at the beginning of the ditch being most likely to be recaptured in the well.

An incremental “particle counter” attribute was implemented in the transport model as a means to determine if and how often modeled tritium particles are captured in RNM-2S, discharged into the ditch, and eventually recaptured in RNM-2S, establishing a pattern of tritium recirculation. The results of this tritium counter calculation are shown in Figure 11 in which the total mass (in moles) of tritium is plotted as a function of the number of captures in RNM-2S at the end of the 1,000-y simulation. Here, it is clear that a majority of the initial 2.08 moles tritium (or 74%) reached the pumping well once during the simulation (corresponding to a value of 1 on the x-axis) and that smaller fractions either did not make it (19%, corresponding to a value of 0 on the x-axis) or made multiple passes between the pumping well and ditch system (or 7%, corresponding to values greater than 1 on the x-axis). In this particular simulation, a very small fraction of tritium (7.9×10^{-5}%) was captured by RNM-2S five separate times (thus making a complete loop as many as four times).

5.4 Longer Term Results and Implications for other Test-Related Radionuclides

The recirculation results clearly suggest that the interpretation of the recovery curves for tritium in Figure 2 must account, at some level, for the potential of recirculation behavior between the ditch and pumping well. Clearly, the model suggests 7% of the initial inventory has been pumped and discharged to the ditch more than once.

The same might be said for interpreting the recovery curves of other radionuclides that have reached the well. For ^{36}Cl, ^{99}Tc, ^{106}Ru and ^{129}I, they are both mobile in groundwater and capable of reaching the pumping well and returning to the water table through the vadose zone. As with tritium, pumping would serve to redistribute them from the localized cavity area to broader areas of groundwater underlying the ditch and playa. Their initial mobile fractions in the cavity area, excluding fractions bound in melt glass and assuming a similar initial distribution, would likely be captured and recirculated in the same proportions as tritium.

^{85}Kr and ^{14}C are mobile and also capable of reaching the pumping well but are unable otherwise to infiltrate back to the water table. ^{85}Kr would evaporate once discharged the ditch, and evidence suggests ^{14}C reacts and is captured in the vadose zone. The net capture of ^{85}Kr and ^{14}C initially available in cavity area groundwater would probably be close to 74% of their initial mobile portions, in analogy with the fraction of tritium captured on the first pass in Figure 11. Hence, pumping served to redistribute much these radionuclides into the atmosphere or unsaturated zone, but not back to groundwater.

Although other radionuclides exist within the cavity environment of the CAMBRIC test (Smith, 1995; Smith et al., 2003), most are largely unavailable for immediate migration, as they are either (1) bound in melt glass, (2) subject to large chemical retardation effects in the saturated alluvium, or (3), both (Tompson, et al., 2006). Thus, their overall migration behavior in the short term would likely be minimal and unaffected by the pumping test and ditch discharge processes.

6. On The Evolution Of Apparent Groundwater Age

The simulations of tritium migration in groundwater and tritium recirculation through the ditch and vadose zone suggest that a comparison can be made between the apparent tritium-based groundwater ages determined in the CAMBRIC system (Tompson et al., 2006) and corresponding ages suggested by the model. As a means to do this, an additional particle attribute was added in the SLIM model to integrate or "count" the continuous period of time each tritium particle spends in a saturated state during its trajectory through the aquifer system. The attribute is reset to zero whenever the trajectory leaves or remains outside a zone of complete saturation (e.g., when $S < 0.95$), and naturally restarts when a trajectory reenters a saturated area (when $S > 0.95$). In this way, the collection of simulated tritium particle ages can be compared with the tritium-based groundwater ages that are essentially a measure of the time that a parcel of groundwater has been removed from atmospheric exposure. This process will naturally adjust particle ages for travel paths that pass through the vadose zone under partially saturated conditions.

Figure 12a shows the spatial distribution of ages, in years, associated with simulated tritium particles in the aquifer system in 1985, approximately twenty years after the test and at a time when pumping was still occurring. The colors represent the simulated age of tritium particles, ranging here between 0 and 35years. Clearly, a large distribution of "young" tritium mass (~ 5-7 y) has accumulated in the saturated zone beneath the ditch, and an "older" distribution of tritium mass (~ 20 y) is still resident in the immediate cavity area. The particles also show accumulations in perched regions above the water table and below the trench where saturations (S) rise above 0.95. By definition, particles resident in areas where saturations (S) are less than 0.95 have a zero age and are not plotted.

Figure 12b shows the spatial distribution of ages in 2000, approximately 35 years after the test, at a time after the cessation of pumping. In this figure there is a wider distribution of tritium particle age associated with significant transport in the saturated zone laterally away from the trench. This is due to the large mounding caused by drainage from the unsaturated zone underlying the ditch. Particles in the cavity region age reflect mixed residence times, some going back 35 y to the initial configuration, and some representing recirculated mass. Subsurface heterogeneity induces significant mixing effects as shown by younger (~ 5y) and older (~ 20y) tritium particles in close spatial proximity.

Figure 13 plots the distribution of simulated particle ages as a function of time observed over the screened interval of pumping well RNM-2S. Symbols lying along the dashed, 45-degree line represent tritium particles that have had no exposure to the atmosphere or unsaturated conditions since the date of the test – that is, particles that have traveled directly from the cavity to the well only once. Symbols plotted below this line correspond to tritium particles that have had some exposure to the atmosphere or unsaturated conditions. Clearly, there is a wide distribution of particles that occur in this age category. Younger particles begin to arrive in 1982 (with an accumulated age of almost 3 years) and represent tritium mass originally pumped from the cavity that has been recirculated through the vadose zone. The difference between the earliest recirculated arrival time (1982) and the earliest direct circulation arrival time (1978) indicates that water pumped into the ditch took approximately 3.5 years to travel back to the well. The vertical scatter in the recirculated particle ages through 1991 demonstrates a distinct mixing phenomenon associated with the pumping conditions. Beginning in 1992, after the pumping well was turned off, the ages generally increase more evenly along 45-degree paths in the plot, indicative of much less mixing. Also, the observed range of isotopically determined groundwater ages measured in this well in 2000 (Tompson et al., 2006) fairly well represent the simulated age distribution.

Figure 14 shows a corresponding distribution of simulated particle ages as a function of time observed over the screened interval of monitoring well UE-5n. This plot also contains a dashed, 45-degree line corresponding to the progression of age from the original test, but clearly no simulated ages fall along this line. The age distributions start in 1985, 6.5y after the start of pumping, with ages of around 5 years, and indicate that water took approximately 1.5y to travel through the vadose zone. The vertical scatter in Figure 14, again indicating a mixing of different aged particles, is similar to that seen in Figure 13 for the pumping well, a range of approximately 10 years. However, for UE-5n there is still significant mixing after the pumping well is turned off while the unsaturated zone below the ditch drains. Again, the isotopically determined groundwater age measured in this well in 2000 (Tompson et al., 2006) falls within the simulated age distribution, although it represents an average of particles collected over the entire screened interval of the well.

7. Summary and Conclusions

A sixteen year pumping experiment designed to examine radionuclide migration away from an underground nuclear test in the saturated zone gave rise to an unintended second experiment involving radionuclide infiltration through the vadose zone, as induced by seepage of pumping effluents beneath an unlined discharge trench. In this paper, the combined experiments have been reanalyzed using a detailed, three-dimensional numerical model of transient, variably saturated flow and mass transport in porous media.

In order to properly resolve flow and transport processes in the heterogeneous sediments that comprise the saturated and vadose zones in the test and ditch discharge areas, the model employed grid refinement and a range of geologic information to both conceptualize and parameterize the model system. The combined flow and transport models were applied over several specific time periods reflecting 10 years of ambient flow following the underground test, two separate intervals of pumping and associated discharge over a 16-y period, and a 40-y recession period of drainage from the vadose zone leading back to a return of the original ambient flow conditions, all of which collectively spanned a period of 66 years.

Importantly, model development was guided by 30 years of geologic, hydrologic, and radiochemical data, and observations collected at the experimental site, a multi-well aquifer test, as well as numerous other models that have been applied at the site. Specifically, the model was evolved to (1) correspond with aquifer test results, (2) match observed ditch inflow rates, (3) reproduce water-mounding observations under the ditch, (4) replicate radionuclide elution data at the pumping well, and (5) simulate radionuclide observations in monitoring wells.

Model predictions of mass transport were able to (1) clearly demonstrate radionuclide recycling behavior between the ditch and pumping well, previously suggested by isotopic age dating information, (2) match travel time estimates for radionuclides moving between the ditch, the water table, and monitoring wells, (3) provide more realistic ways in which to interpret the pumping well elution curves, and (4) illustrate the complexities and details associated with migration through a heterogeneous system under both saturated and unsaturated conditions.

Overall, the results provide a clearer picture as to how the pumping experiment and ditch recharge led to a more dispersed source of certain mobile radionuclides in groundwater near the CAMBRIC test.

The ability to examine the combined influence of saturated and unsaturated flow behavior on mass transport in the heterogeneous system considered was facilitated through the use of accurate and efficient large-scale simulation codes. Collectively, these findings illustrate the utility of integrating detailed numerical modeling with diverse observational data in developing accurate interpretations and forecasts of contaminant migration processes.

ACKNOWLEDGEMENTS

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Figures and Figure Captions

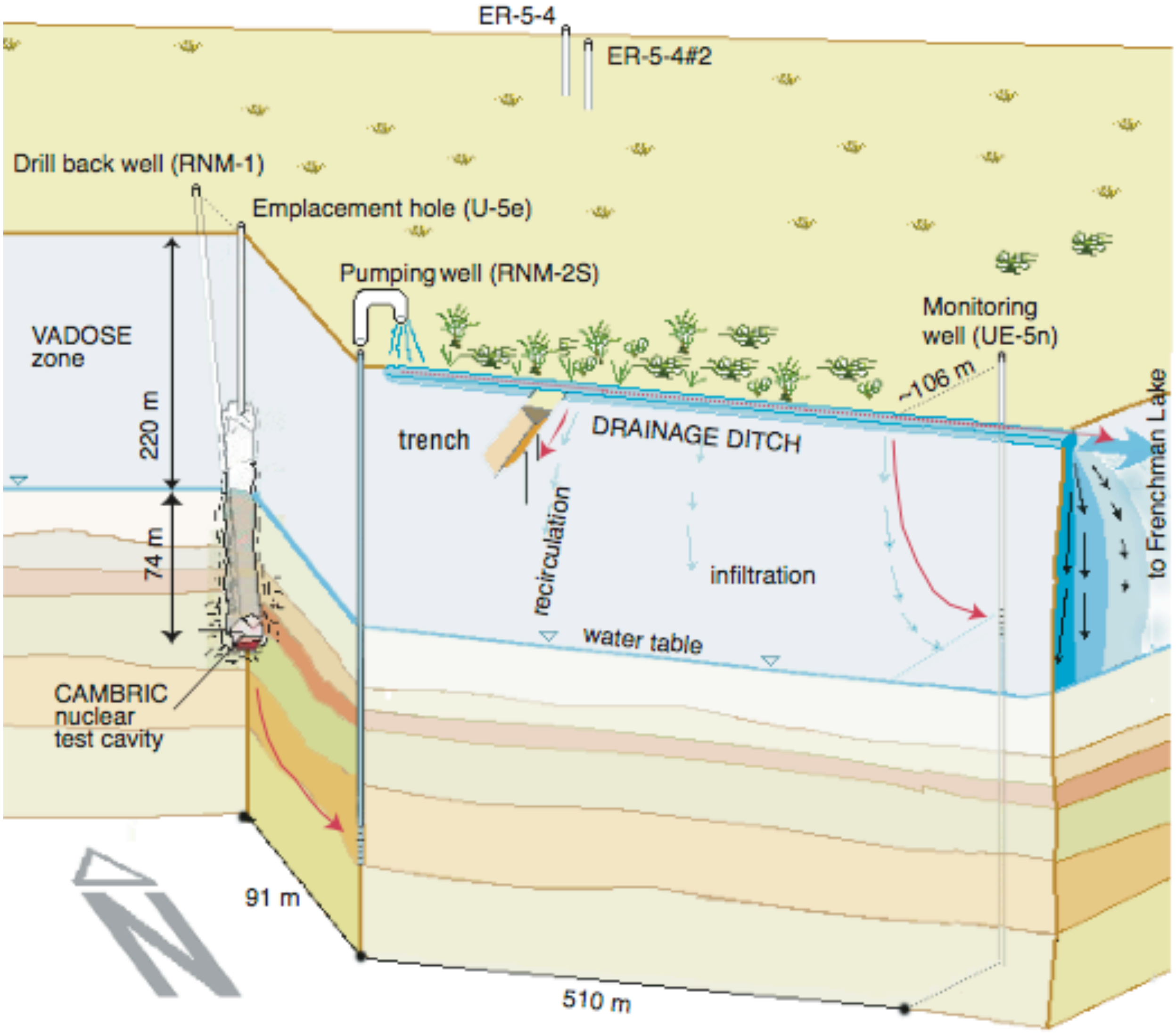


Figure 1: Schematic of the CAMBRIC test area in Frenchman Flat at the NTS, showing the test emplacement hole (U-5e), cavity and collapsed chimney, pumping well RNM-2S, drainage ditch, lysimeter trench, and monitoring wells UE-5n, ER-5-4, and ER-5-4#2. Known tritium pathways are shown in red.

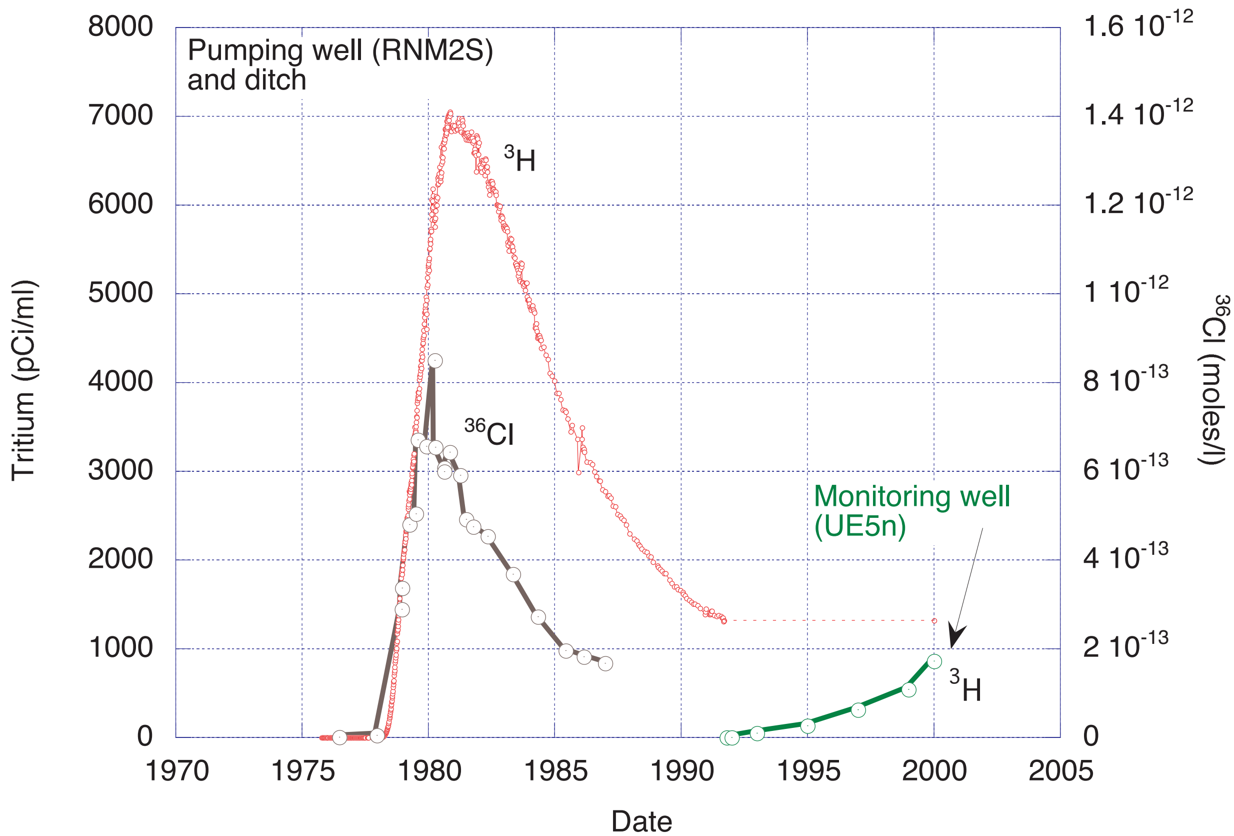


Figure 2. Tritium (^{3}H) activity and ^{36}Cl concentrations observed in the pumping well (RNM-2S) between the initiation (1975) and cessation of pumping (1991), and in an isolated measurement made in 2000. Rising tritium activity in monitoring well UE-5n beginning in 1991 is also shown. All data are decay corrected to May 14, 1965.

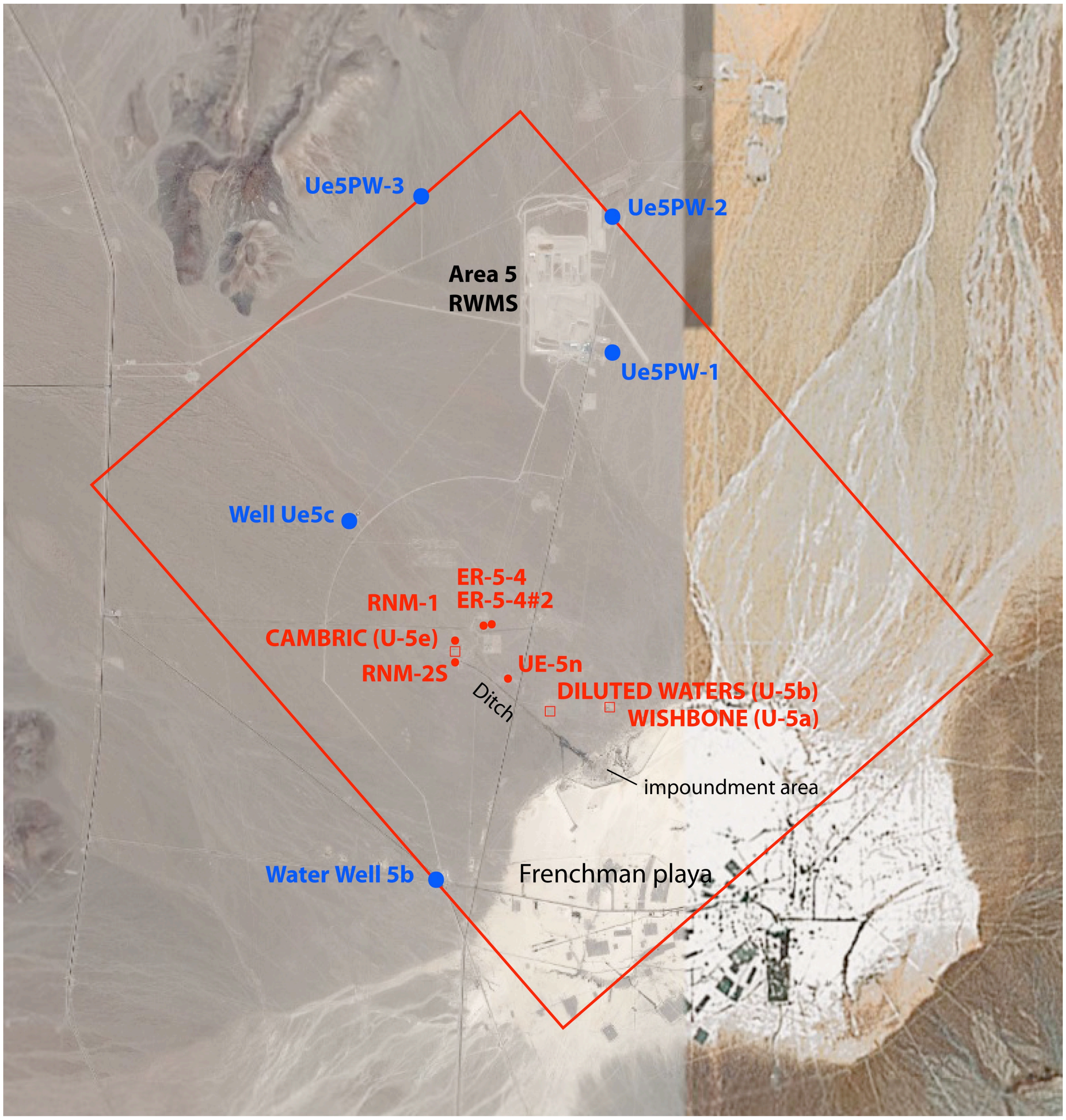


Figure 3. Aerial view of Frenchman Flat, NTS, showing locations of CAMBRIC (U-5e), nearby boreholes and monitoring wells, the CAMBRIC ditch, as well as DILUTED WATERS (U-5a) and WISHBONE (U-5b) tests. The red box indicates the horizontal extent of the model domain used for simulations.

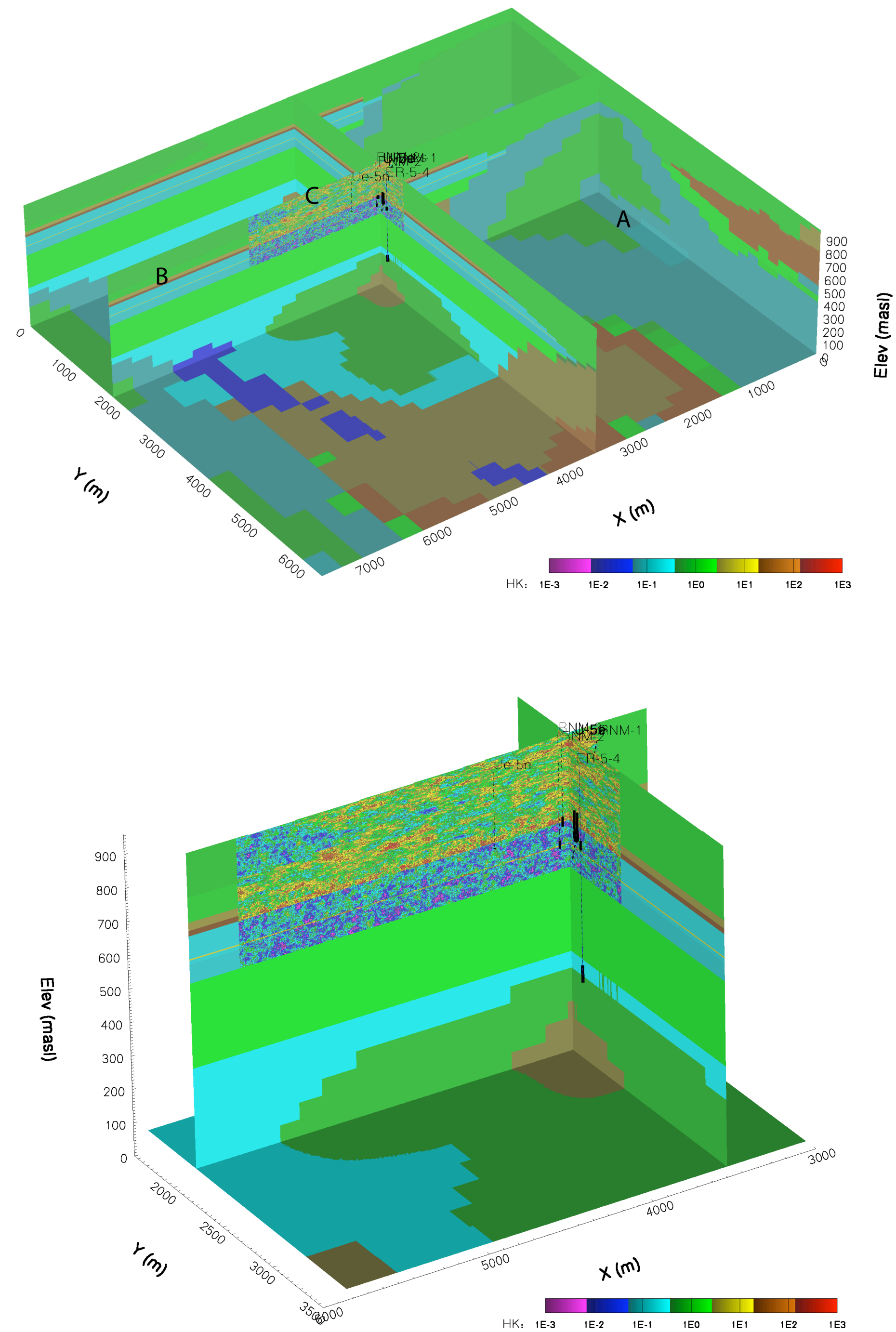


Figure 4. Upper panel: hydraulic conductivity field used in the ParFlow model with the coarse grid region (A), the subdivision of alluvial layers (B) and the fine resolution mesh region (C). Lower panel: detailed view of the fine-mesh region.

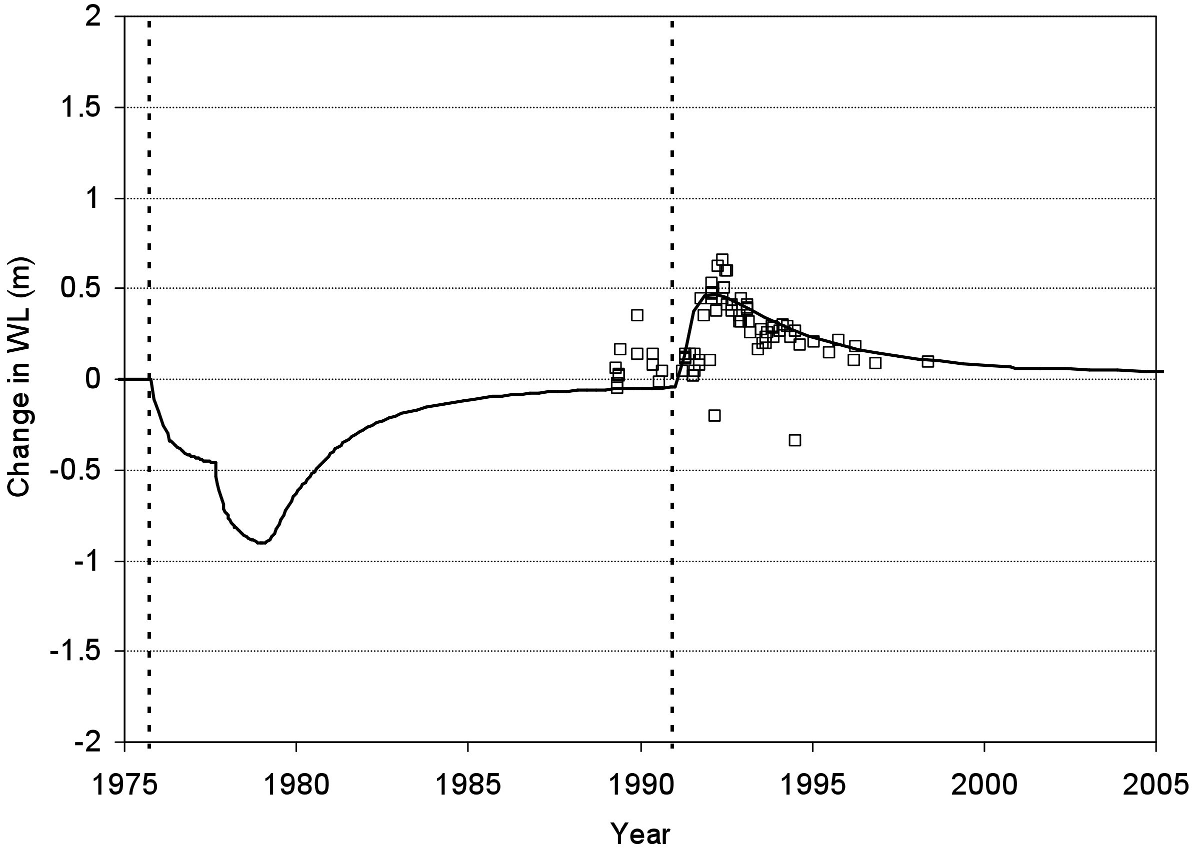


Figure 6. Plot of simulated (solid line) and observed (symbols) water level change from ambient conditions for the observation location UE-5N.

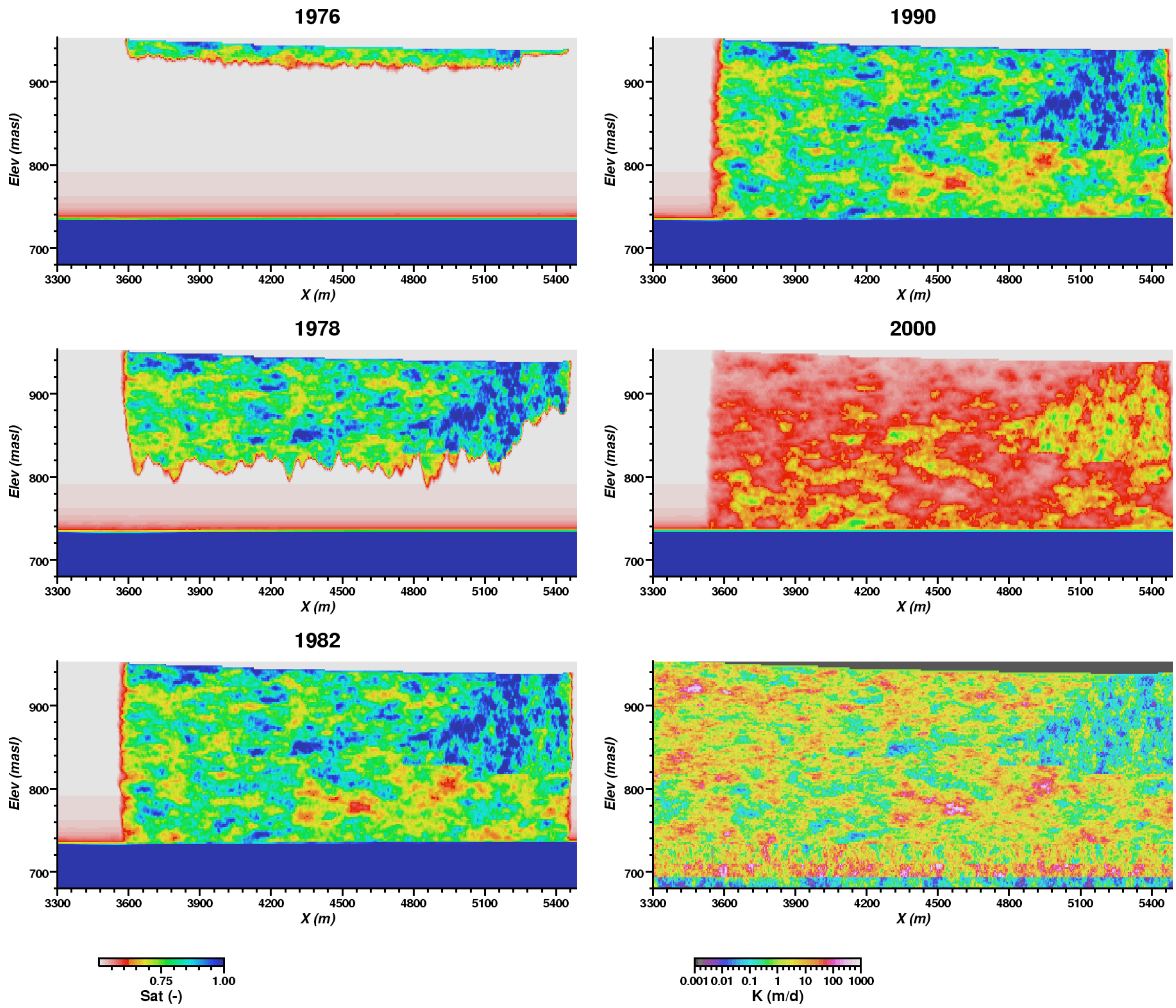
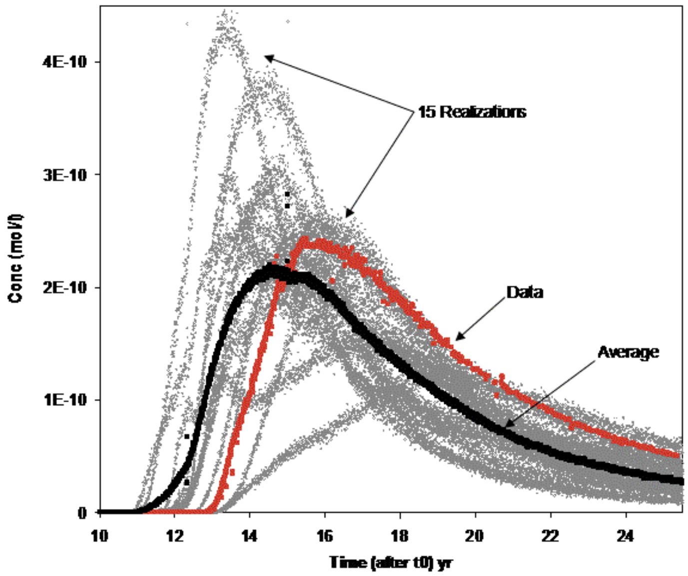
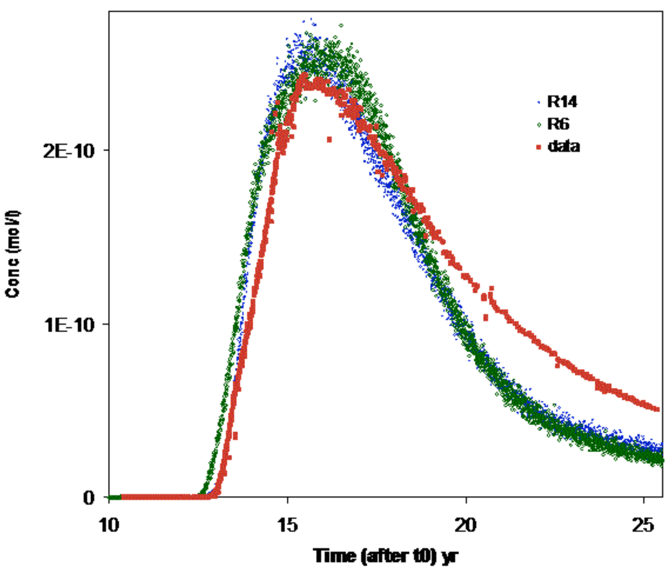


Figure 7. Plot of simulated saturation along the centreline of the ditch at several points in time, after the start of pumping in 1976 along with the saturated hydraulic conductivity along the same plane. Note that pumping ceased in 1992 and the plot for the year 2000 is during the drainage of the vadose zone under the ditch.



A



B

Figure 8. (a, top) Observed (red) and simulated (gray) breakthrough of tritium at RNM-2S based upon 15 realizations of hydraulic conductivity in the fine resolution area of the ParFlow model (all decay-corrected). The black curve represents the average of the 15 simulated curves; (b, bottom) Observed (red) and simulated breakthrough of tritium at RNM-2S for the two best-fit realizations, R14 (blue) and R6 (green), of hydraulic conductivity in the fine resolution area of the ParFlow model.

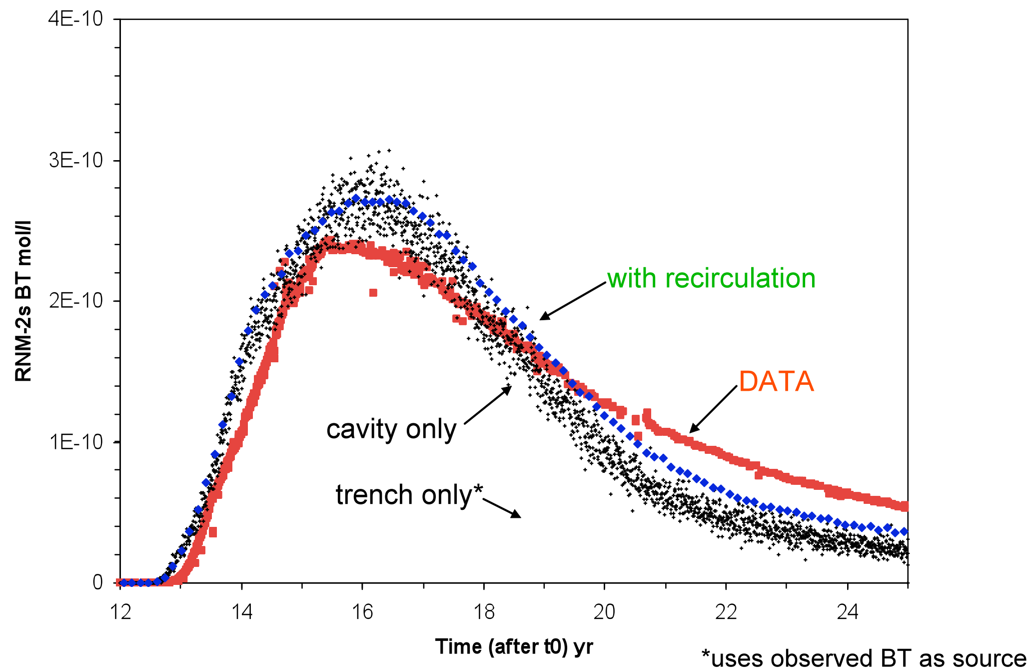


Figure 9. Four decay-corrected tritium breakthrough profiles at RNM-2S obtained from (a) measured data and simulations that (b) excluded ditch recharge, (c) included ditch recharge and allowed for recirculation, and (d) were based upon ditch recharge only, using the measured elution curve as input with no initial cavity source.

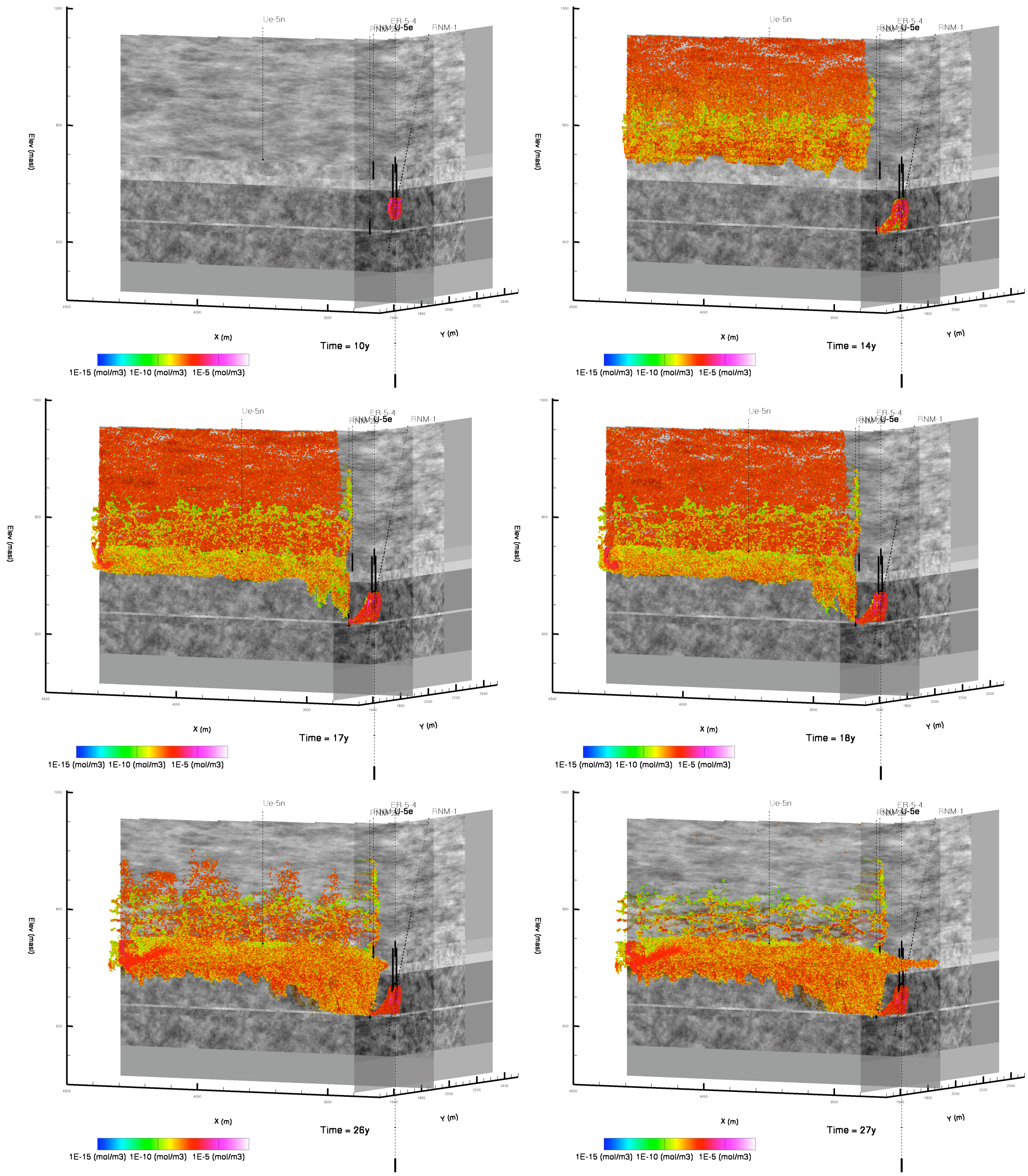


Figure 10: Decay-corrected tritium concentrations at different points in time during the simulation (10.4, 14, 17, 18, 26, and 27 y, from top left) focused on the region near the cavity. The upper left panel represents tracer transport after 10.4 y of ambient migration, just before the onset of pumping. The last panel represents tracer transport at 27 y, 2 y after the cessation of pumping. Note the pathway from cavity to well and from ditch to water table.

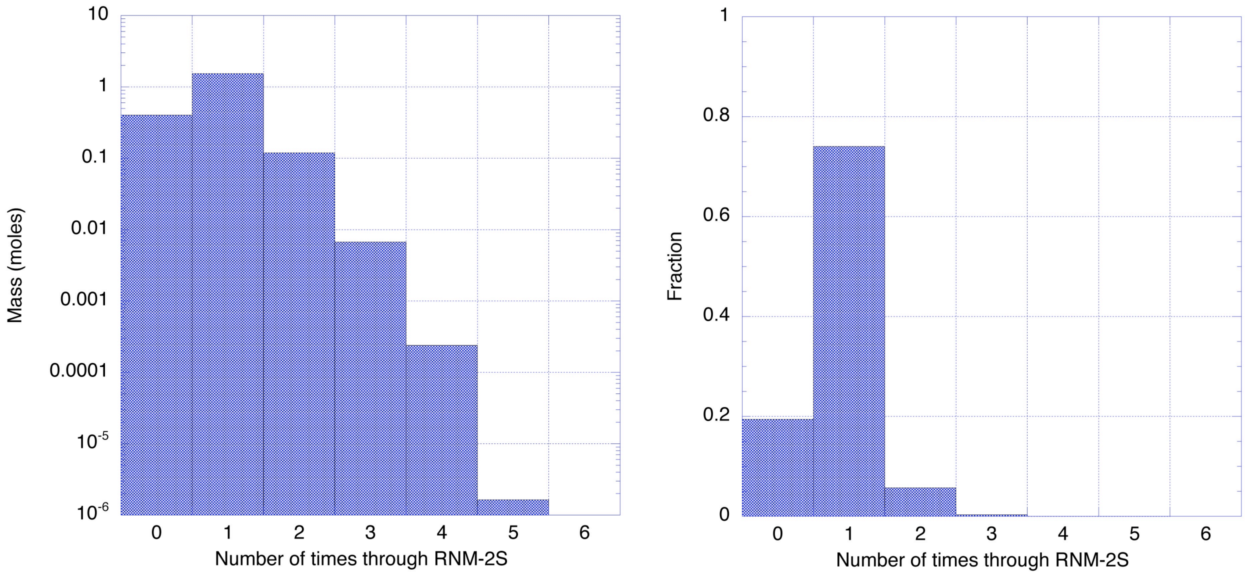
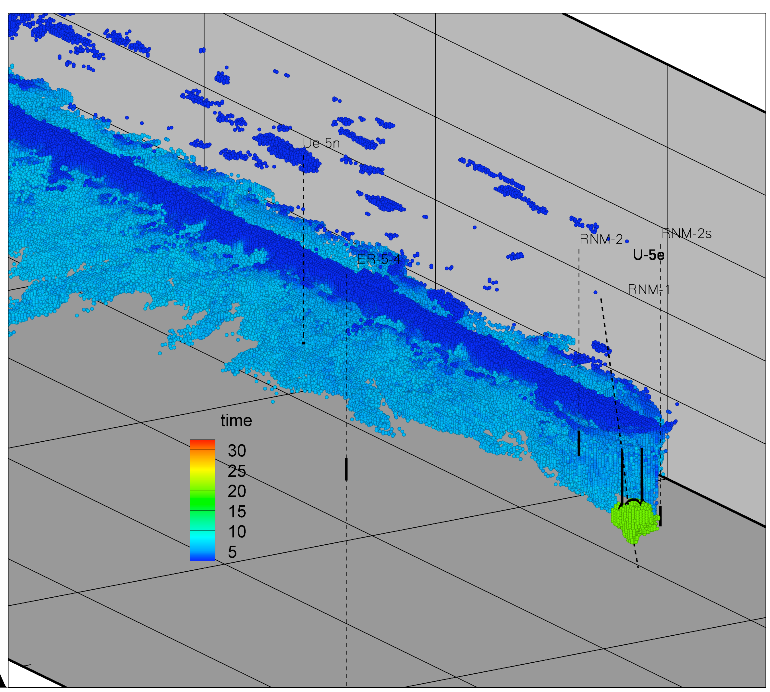
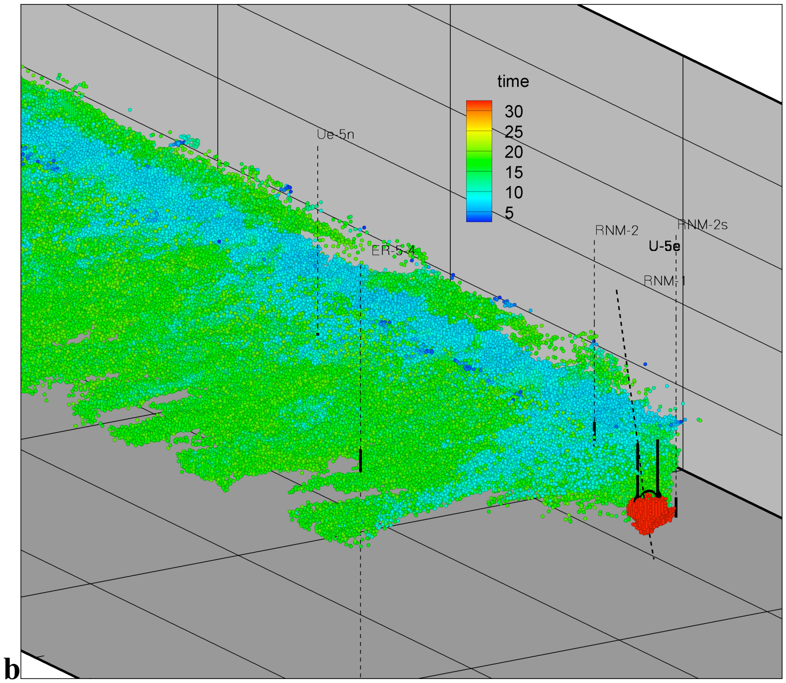


Figure 11. Decay-corrected mass of tritium (left) or fraction of initial tritium mass (right) captured by pumping well RNM-2S as a function of the number of times mass was captured by RNM-2S; . The total tritium mass considered is 2.08 moles (Hoffman et al., 1977).

A





b

Figure 12, plot of simulated tritium age, in years, as calculated by the particle tracking model (a) for the year 1985, corresponding to approximately 20 years after the test, while pumping was ongoing, and (b) for the year 2000, corresponding to approximately 35 years after the test during the recession and drainage time period. View is from the north toward the south, with the CAMBRIC cavity in the foreground, and with the ground surface approximately coplanar with the tops of the indicated well columns.

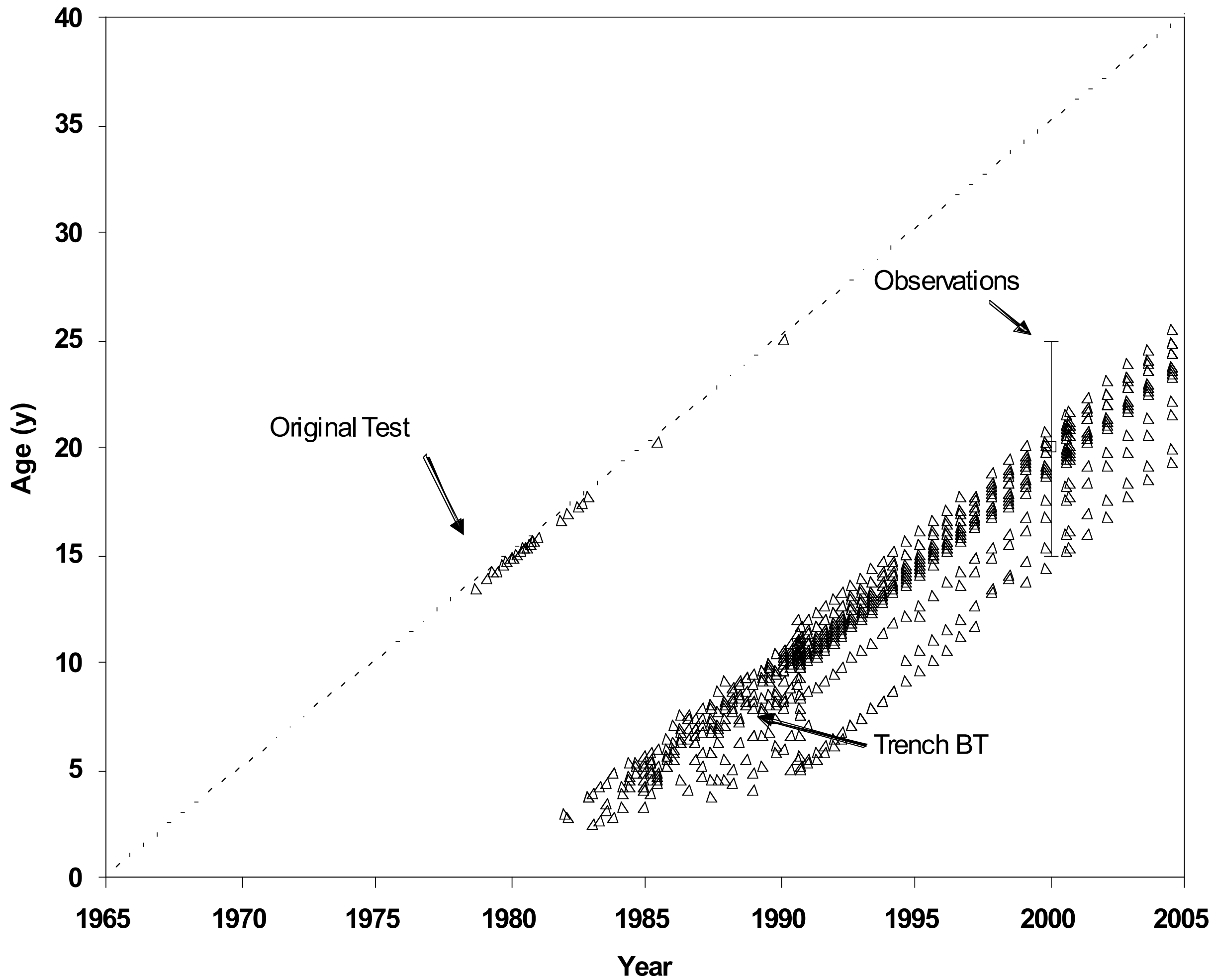


Figure 13. Plot of simulated tritium particle age as a function of time from water collected in the screened interval of pumping well RNM-2S. Particle ages lying on the dashed, 45-degree line correspond to tritium particles that have moved from their initial cavity locations cavity to the well only once. Particle ages below this line have reduced ages owing to atmospheric exposure. The distribution of isotopically determined groundwater ages measured in 2000 is also shown.

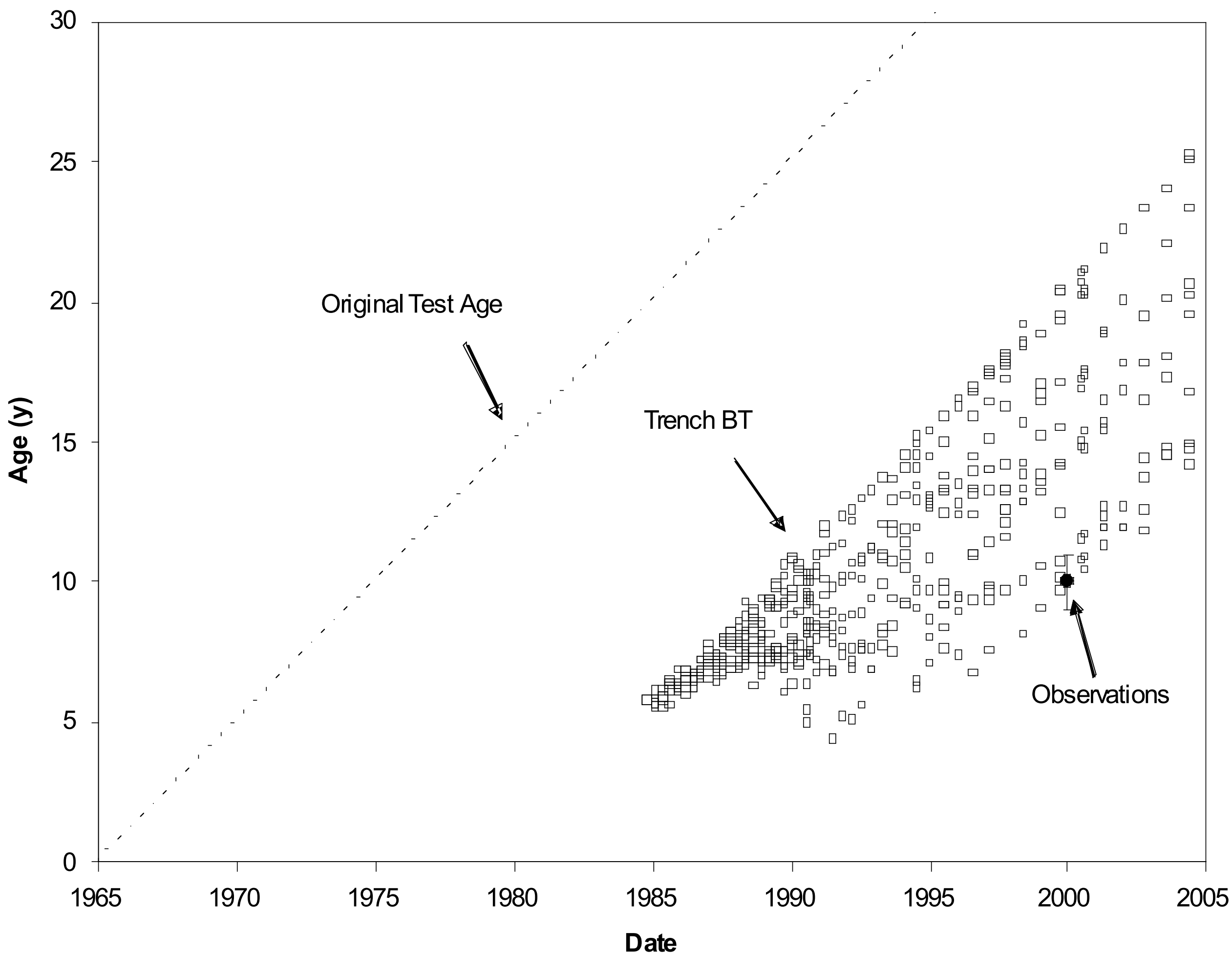


Figure 14. Plot of simulated tritium particle age as a function of time from water collected in the screened interval of monitoring well UE-5n The dashed, 45-degree line corresponds to water with a tritium age corresponding to the date of the original test. Particle ages below this line have reduced ages owing to atmospheric exposure. The isotopically determined groundwater age measured in UE-5n in 2000 is also shown.